AN INDIRECT-CYCLE NUCLEAR-REACTOR SYSTEM TO FURNISH PROCESS HEAT-- ENGINEERING AND DESIGN CONCEPTS

BY R. CARSON DALZELL AND JAMES P. McGEE

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by

R. Carson Dalzell[2/] and James P. McGee[3/]

SUMMARY

The use of nuclear fission for chemical process heat offers the special advantage of high temperature, limited only by materials of construction. The process heat may be supplied economically at elevated pressures, since no compression of combustion air is required. For the initial effort in developing a high-temperature reactor, the indirect cycle, using helium as the heat-transfer medium, was chosen. The major problems are the design of high-temperature fuel elements, construction of an exchanger to transfer heat to process streams in the range of 2,500° F., and development of compressors capable of recycling helium at 1,000° F. and above.

A conceptual design of a nuclear reactor to furnish process heat for coal gasification has been made. Spherical fuel elements utilizing a graphite structure, impregnated with uranium carbide fuel, were chosen, as spheres offer the possibility of easier loading and unloading of the reactor. Calculations of pressure drop and gas-pumping power for the system are included.

A study of the design criteria and possible materials of construction for the heat exchanger (coal gasifier) was conducted; however, the detailed design of this equipment is beyond the scope of this paper.

The conditions of operation for the recycle compressor to circulate the helium through the system have been reviewed. Although such a machine is not currently available, experience with gas turbines operating at even higher temperatures should be applicable.

Pressures, temperatures, and heat duty for a projected commercial system to gasify 120,000 pounds of coal per hour have been calculated. To gasify this quantity of coal would require one 250-thermal-megawatt reactor, the size chosen for this design study.

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INTRODUCTION

Although nuclear reactors have been constructed for research and testing, electric power production, and propulsion, the direct utilization of nuclear heat to promote a chemical process has not yet been developed. However, use of nuclear heat for that purpose is attractive; and the Atomic Energy Commission, the Bureau of Mines, and several major chemical companies have considered this source.

There are several advantages in using energy produced by nuclear fission for supplying chemical process heat. Temperatures that can be achieved are limited only by materials of construction, since there is no inherent limiting temperature, as in the combustion of hydrocarbon fuels. Nuclear heat can be obtained at elevated pressures, and there is no combustion air to compress. The balanced recycle operation reduces heat losses, since there are no stack losses.

A number of processes that could use nuclear heat have been proposed by Daniels (3),4/ Graham (5), Strimbeck, McGee, and Katell (9), and others. The processes considered include cracking natural gas, direct nitrogen fixation, production of acetylene, hydrocyanic acid production, coal gasification, oil-refinery processes, and high-temperature steam superheating.

Process heat reactors fit into three general classes:

1. Direct cycle. - All of the process streams passed through and reacted within the nuclear reactor.

2. Process-stream preheating. - One or more of the process streams preheated in the nuclear reactor and subsequently reacted by direct contact in a separate reaction vessel.

3. Indirect process cycle. - An inert gas such as helium heated in the nuclear reactor and subsequently giving up its heat to the process streams by indirect heat exchange in a separate reaction vessel.

These possible types of nuclear reactors have been described by Graham (5). All three types have individual advantages. If satisfactory ceramic fuel elements can be developed, capable of containing the fission products, the direct cycle reactor should be attractive for processes that are favored by neutron and gamma irradiations and where induced radioactivity in the product stream is not a problem. Also, if suitable ceramic fuel elements and refractories are developed, preheating of process streams such as air or steam to 3,000° F. and above should solve many industrial requirements for process heat. However, it appears that considerable research and development will be required to perfect such nuclear fuel elements. Furthermore, a great many operating problems need to be solved, owing to the unprecedented temperature levels involved.

4/ Underlined numbers in parentheses refer to items in the bibliography at the end of this report.

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Operation of a reactor in this temperature range would represent a considerable advance in reactor technology.

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PART I

Nuclear Process Heat for Chemical Reactions

The first approach to the use of high-temperature nuclear heat for processing would seem to be a system that imposes the least restrictions on the reactor design. The indirect process cycle, using helium as the heat-transfer medium, appears to offer the most promise from this viewpoint.

Gas-cooled reactors have been proposed by a number of researchers in the field. The Daniels pile, one of the first attempts to utilize nuclear heat for power generation, was designed in 1946. This reactor concept would use helium to transfer heat to water for generating steam. Since that time, Daniels and others have proposed gas-cooled reactors as a source of heat for both steam and gas turbine plants. Daniels' latest design, which is proposed for a gas-turbine cycle, appears to be equally adaptable as a source of process heat.

The use of a gas as a heat-transfer medium has two fundamental disadvantages: (a) The overall heat-transfer coefficients are considerably lower for gases than for liquids; and (b) to remove a given amount of heat, the energy required to recirculate a gas is usually higher than that required for a liquid. Also the reactor volume will be greater when a gaseous coolant is used. However, recent developments in high-temperature technology seem to point toward gas-cooled reactors, since gases have been used for a number of years as heat-transfer media at temperatures up to 4,000° F.

Process Heat-Reactor System

A system using the indirect cycle will consist essentially of a nuclear reactor to heat the gaseous heat transfer medium; a high-temperature heat exchanger to transfer heat from the gas to the process streams, and a recycle compressor to recirculate the carrier gas (fig. 1).

Choice of Inert Gas

The criteria for choosing the gaseous heat-transfer medium are:

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1. Heat-transfer properties.
2. Pumping power requirements.
3. Nuclear properties.
4. Chemical properties.
5. Cost.
6. Availability.
7. Purity.

Helium meets the requirements better than any other gas. Its cross section for neutron absorption is negligibly small. It has a high specific heat and low pumping power requirement and is chemically inert. The specific heat of hydrogen is more than double than that of helium, and the power requirements would be the lowest for any gas. However, from a chemical standpoint, hydrogen is not acceptable because it reacts with graphite in the 1,000° to 2,500° F. range. Other gases considered were nitrogen, carbon dioxide, and argon. Carbon dioxide also reacts with graphite in the range of 1,000° to 2,500° F. This would eliminate the use of unclad graphite as a moderator in the reactor. Argon has a low specific heat that makes pumping costs prohibitive. It also forms the radioactive isotope, A^{41}, which would be difficult to separate. When irradiated, nitrogen forms the radioactive isotope, C^{14}, which has a long half-life. It also reacts unfavorably with ferrous metals at high temperatures, forming nitrides, and has a relatively low specific heat. The properties of the various gases are shown in table 1.

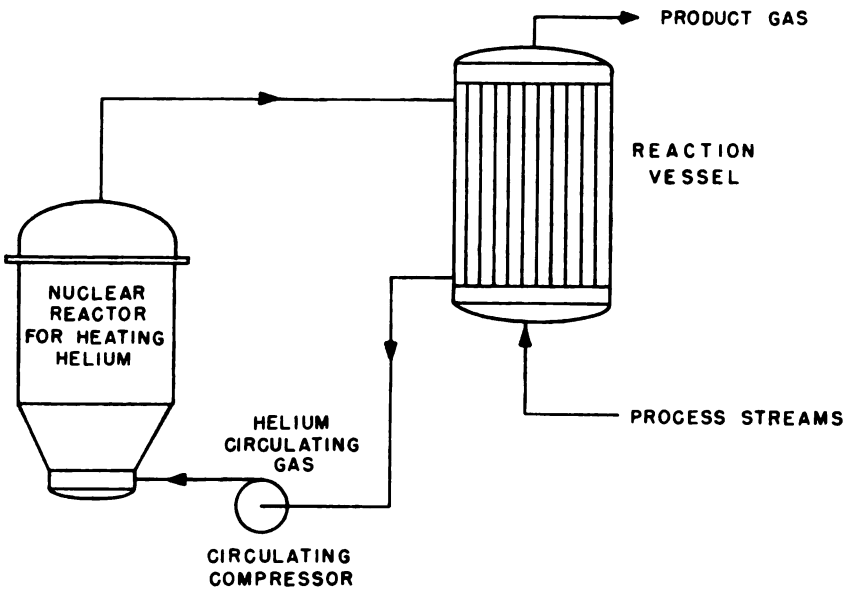

FIGURE 1. - A Simplified Helium Recycle Flowsheet.

Helium has the disadvantage of being expensive and limited in supply. Most of the helium now being produced comes from natural gas in the vicinity of Amarillo, Tex. Current production is about 280-million cubic feet annually. To obtain this helium, approximately 2.5 percent of the helium-bearing natural gas now going to market is being processed. The helium in the natural gas not processed is lost. Further demands for helium would require more plant capacity for processing additional quantities of natural gas.

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TABLE 1. - Properties of gaseous coolants

Gas	Molecular weight	Specific volume, cu. ft./lb.	Specific heat, C_p B.t.u./lb.°F. at 2,500° F.	Nuclear properties		Chemical properties
				Thermal absorption cross section, barns		
Argon	40	9.5	0.124	0.62	Forms radioactive argon 41	Inert.
Carbon dioxide	44	8.54	.336	.003		Reacts with graphite at high temperatures.
Helium	4	95.2	1.24	.007	Inert	Inert.
Hydrogen	2	187.9	3.94	.32		Reacts with graphite at high pressures. As temperature increases, extent of reaction decreases. Reacts with uranium compounds.
Nitrogen	28	13.5	.291	1.7	Forms radioactive carbon 14	Reacts with ferrous metals at high temperatures.

The quantity of helium required by a reactor system probably will be in the range of 1 cubic foot of gas per thermal kilowatt of capacity. Due to the high cost of helium, it is obvious that gas-cooled reactors using helium must be virtually gastight, even if the fuel element retains the fission products. Also, provisions must be made for draining the system and storing the helium during refueling and maintenance.

Factors Influencing Design of a Process Heat Reactor

A limited study has been made to obtain some idea of the physical dimensions of a reactor supplying process heat. It appears that the heat-generating capacity of a nuclear reactor employing a gaseous coolant will be limited by the diameter of the pressure shell that contains the core. The most economical

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high-temperature reactor probably will be governed by the size of the largest pressure shell that can be shop-fabricated and shipped to its destination. In the opinion of designers of large pressure vessels, the ratio of cost of field fabrication to shop fabrication may vary from 2:1 to 3:1. The actual location of the reactor site will allow some variation in the maximum size that can be transported. If transportation by water is feasible, the maximum vessel size that can be shop-fabricated and transported can be increased appreciably.

The choice of core design will have a definite bearing on reactor-shell dimensions. Since a detailed design would depend on numerous variables, many of which are unknown at present, only approximations can be made with regard to heat transfer and pressure drop.

For the purpose of this preliminary study, spherical elements were chosen, since most of the heat-transfer and material studies made in the Atomic Energy Commission - Bureau of Mines exploratory program have been with this shape. Other shapes for fuel elements may result in a smaller core for a given output.

Spherical elements have many advantages: (1) It is possible to obtain a large heat-transfer surface per unit of reactor volume; (2) their manufacture is amenable to mass production techniques; (3) the turbulent flow through the bed results in good heat transfer; (4) they are self-supporting and require only a containment structure; and (5) they offer the possibility of loading and unloading the reactor through ports rather than removing the entire vessel top. A disadvantage of spherical elements is high-pressure drop for a specific flow of gas.

Heat transfer and pressure drop through beds of spheres have been studied by a number of investogators (2, 4, 6, 7). The various authors are in fairly close agreement. Choice of sphere diameter for core design is a compromise between heat transfer to the gas and pressure drop across the bed. As the sphere diameter is decreased, both heat transfer per unit of bed volume and pressure drop increase.

A pressure drop across the bed, not to exceed 5 p.s.i., was arbitrarily chosen as reasonable. Calculations indicate that the use of 3-inch-diameter spheres results in approximately 3-p.s.i. pressure drop across the sphere bed. Variation of heat output with core size is shown in figure 2. Figure 3 shows variation of operating pressure with core diameter.

A reactor using 3-inch spherical elements, with helium at 30 atmospheres as the coolant, requires a bed 12 feet in diameter by 10 feet in height for a thermal loading of 250 megawatts. A pressure of 30 atmospheres was chosen, since this pressure is currently used for coal gasification. Such a reactor, after allowing for insulation, would require a pressure vessel 14 feet in diameter. Transportation of this size vessel could be accomplished only in certain locations.

Daniels has proposed a smaller reactor for an indirectly heated gas turbine, employing uranium carbide, graphite, and helium. Although specifying an outlet helium temperature of 1,350° F., he pointed out that with the carbon-uranium carbide-helium system, fuel element temperatures of 3,600° F. appear to be feasible.

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The core of the reactor is insulated from the carbon steel shell by 9 inches of ceramic lining. To protect the shell from high temperatures caused by a possible refractory failure, and to remove heat generated by gamma radiation, a water jacket completely surrounds the shell. The core rests on a molybdenum plate supported by columns from the floor of the vessel. To cool the supports, the inlet helium enters at the bottom of the reactor. If helium inlet temperatures are kept below 1,200° F., the supports can be made of 18-8, type 304, stainless steel. The inlet helium will then act as a coolant to remove heat from the plate and supports.

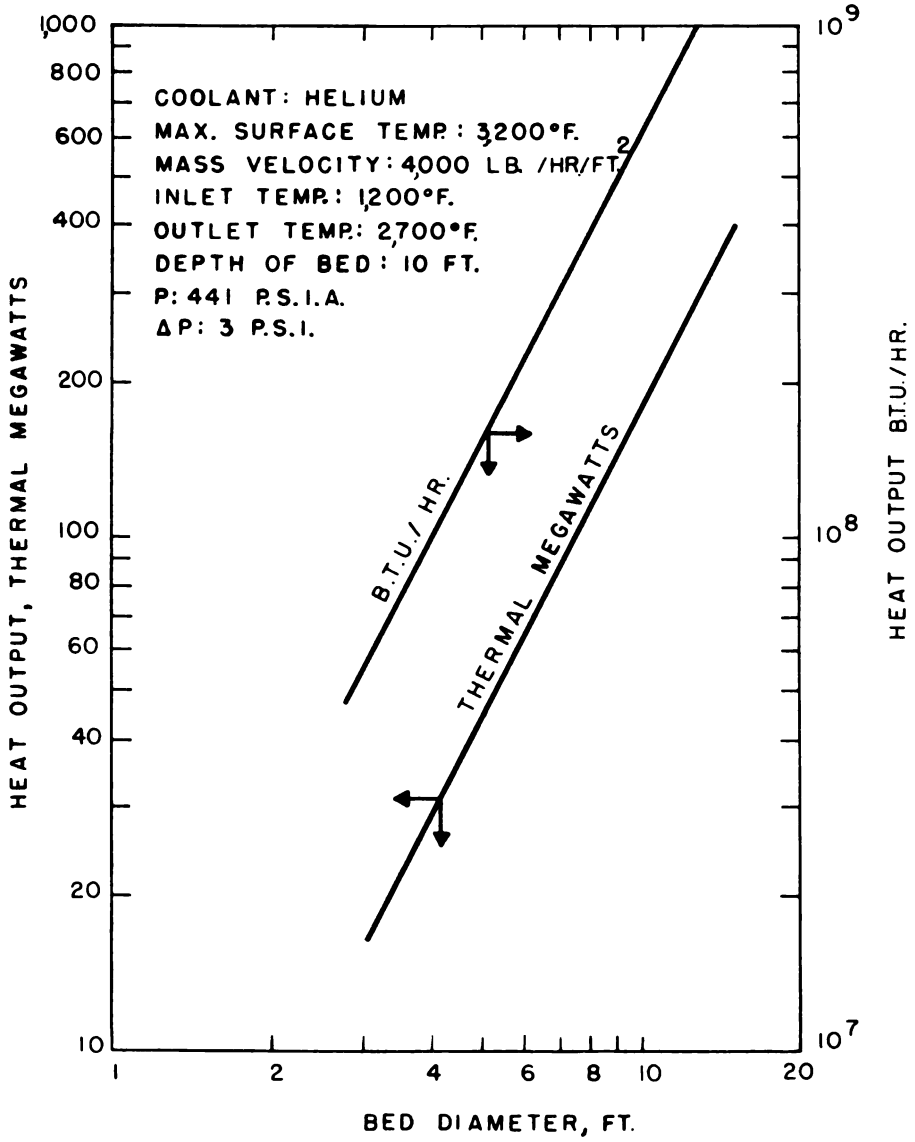

FIGURE 2. - Variation of Heat Output With Bed Diameter (heat transfer from cylindrical bed of 3" spheres).

A precedent for this type of design for vessels for high-temperature processing exists in the Lurgi pressure gasifiers. Water-cooled shells for these gasifiers, which operate with internal temperatures up to 2,400° F. and pressures of 30 atmospheres, have been built in sizes up to 12 feet, 2 inches I.D. and approximately 14 feet O.D., including the water jacket. Nine gasifiers of this size have been installed in the Sasol synthetic fuel plant in South Africa, and reports from that activity indicate that their operation has been satisfactory. The foregoing considerations led to the characteristics summarized in table 2.

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Variation of theoretical pumping power with system pressure drop is shown in figure 4. Although a system pressure drop of 10 p.s.i. has been chosen more or less arbitrarily, it may be impractical, or even impossible, to achieve this low figure.

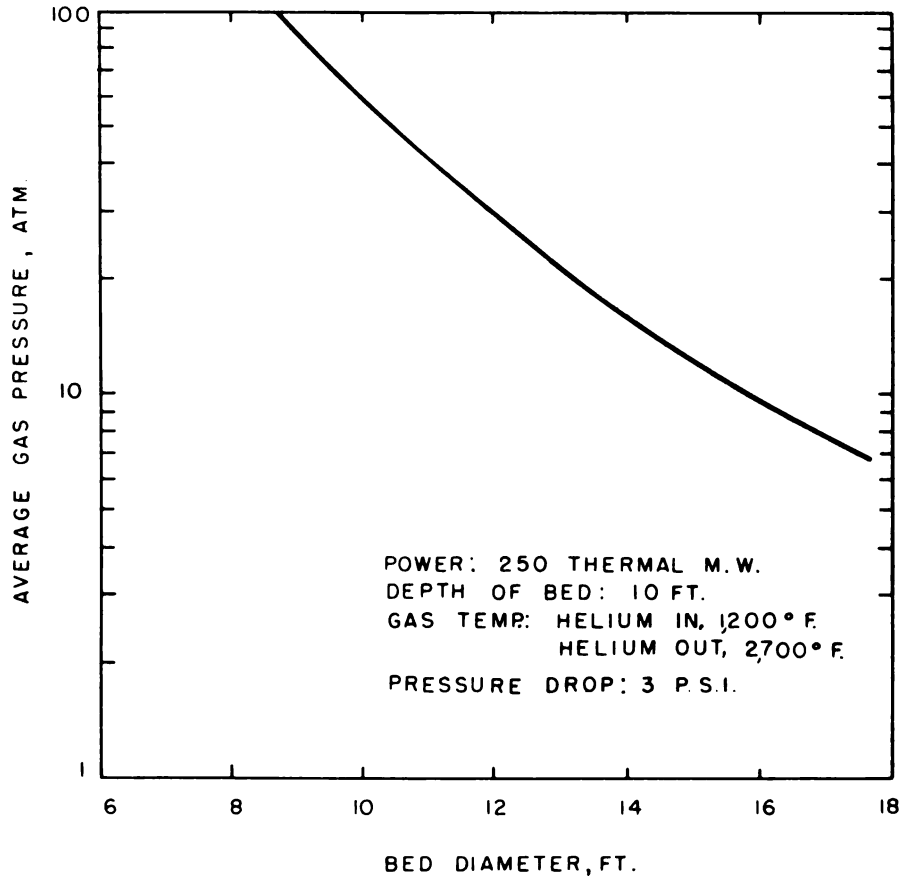

FIGURE 3. - Variation of Operating Pressure With Bed Diameter in a Packed Bed of 3" Spheres.

It is expected that the reactor can be operated on low-enrichment uranium. The choice of enrichment will depend on many economic and engineering factors. These include ease of loading and unloading, economic reward of long refueling cycles, practicability of using burnable poisons, physical stability of fuel elements, retention of fission products, cost of fuel elements, cost of chemical reprocessing, and so on.

High-Temperature Reactor Control

Another major problem in a high-temperature, gas-cooled reactor system is the method of controlling such a reactor.

A gas-cooled reactor does not appear to have an inherent negative temperature coefficient, and increase in temperature does not have a self-regulating effect, as in a water-cooled reactor. In practice, the temperature coefficient may be positive, due to a change in the cross section of xenon with temperature. Xenon undergoes a sharp reduction in cross section in the range of 2,500° F.

Control schemes considered are poison rods, reflector control, and regulation by controlling the amount of gaseous "poisons," such as xenon, in the primary coolant system. Control rods operating in the core would require guide cylinders of carbon or some other ceramic material, permanently installed

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in the bed. Boron carbide, either unclad or encased in a molybdenum sheath, has been proposed for the rod material. The rod-operating mechanism would be hermetically sealed to prevent the escape of helium. It appears that, even with the use of other schemes, some control rods will be required. Movable reflector control offers the advantage of having the moving sections outside the reactor vessel; however, due to the relatively thick pressure-vessel walls and water cooling, the effect of reflector control would be considerably diminished. The possibility exists of installing control rods in the graphite reflector. These would also be subject to the diminishing effects.

TABLE 2. - Reactor system characteristics

Helium inlet temperature: 1,200° F.
Helium outlet temperature: 2,700° F.
Heat generating capability: 250 thermal megawatts = 853×10^6 B.t.u./hr.
Helium flow: 450×10^3 lb./hr.
Pressure in reactor: 30 atmospheres = 441 p.s.i.a.
Fuel elements: 3-in.-diameter spheres.
Core dimensions: 12-ft. diameter, 10-ft. height.
Volume of core: 1,131 cu. ft.
Number of spheres: 90,500.
Area of spheres: 17,700 sq. ft.
Heat flux: 48,000 (B.t.u.)/(sq.ft.)/(hr.).
Refueling period: 350 days.
Pressure drop through reactor: 3 p.s.i.
Pressure drop through entire system: 10 p.s.i.
Ratio of compression: 1.023
Adiabatic head for helium at a pressure ratio of 1.023 and 1,200° F.: 15,000 ft.
Theoretical horsepower: 3,400.
Shaft horsepower: 4,500.

Control by varying the amount of high cross section gas in the reactor coolant system offers possibilities. Xenon is formed as the fuel fissions, and provisions must be made for its continuous removal from the gas stream. Varying the rate of removal of the xenon, combined with pressure storage of a gaseous "poison" that could be used to flood the system in case of a reactor excursion offers the possibility of control with a minimum of rods.

A novel system has been proposed by Schluderberg (8), which consists of dusting or "spiking" the gaseous heat-transfer medium with small refractory particles. Graphite appears to be the first choice. Tests have shown that it is possible to load air with 10 pounds of micronized graphite (1 to 5 microns) per actual cubic foot of fluid. By varying the amount of graphite in suspension, reactor control might be effected by a change in moderator density. In addition, the use of "spiking" should improve the heat-transfer characteristics of the gaseous coolant, with an accompanying reduction in pumping power.

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In general, control by varying the characteristics of the coolant seems to offer greater promise of an operable system than control by mechanical devices.

Reactor System Components

Helium-Purification System

Even with the best fuel-cladding techniques foreseeable in the near future, some fission products can be expected to escape into the helium coolant stream when the fuel elements are operating at temperatures above 2,500° F. This will necessitate using a system to continuously remove radioactive particles and contaminant gases from the circulating helium stream. A side stream of approximately 1 percent or less of the helium can be diverted from the coolest (1,000°F.) portion of the loop, cooled further in a helium-to-helium heat exchanger, and then passed through a system of filters to remove entrained dust particles. Following further cooling to liquid-nitrogen temperature, the xenon can be removed by absorption in charcoal filters. This technology of low temperature helium purification has been used for a number of years by the Bureau of Mines to purify helium on a large scale. It is also in general use in laboratories for refining helium to a high degree of purity. In this system only the heat exchangers, cold traps, and filters would be in a radioactive area. The liquid

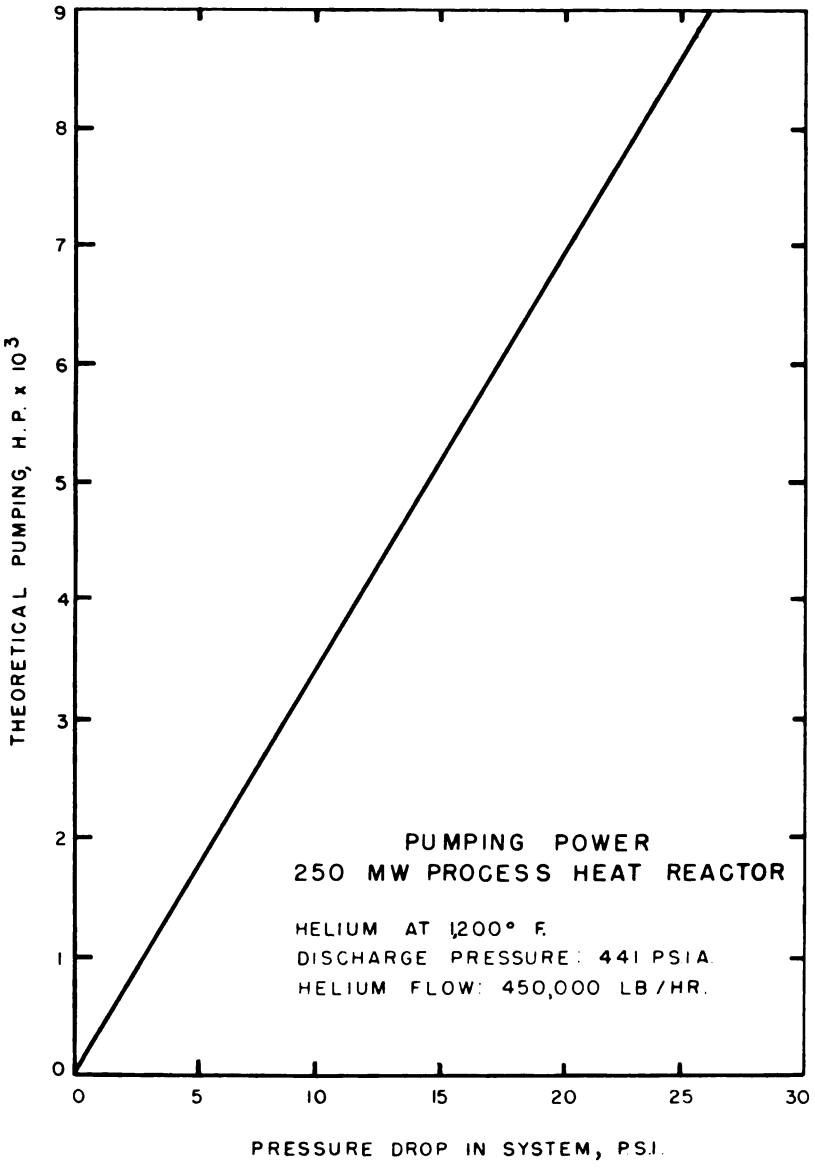

FIGURE 4. - Pressure Drop in System, p.s.i.

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nitrogen would not come into direct contact with the helium. The refrigeration equipment for producing liquid nitrogen would be outside the radiation shield. The nitrogen compressors would not become radioactive and could be maintained in the conventional manner.

With ceramic clad fuel elements, there is the possibility of flaking or cracking of the cladding. To protect the heat exchanger from large particles, a high-temperature cyclone can be installed at the reactor exit so that particles in the size range above 10 microns will be removed.

High-Temperature Recycle Compressor

The recycle compressor is used to circulate the heat-conveying helium through the nuclear reactor and the process heat exchanger. This machine is the only rotating piece of equipment in the high-temperature loop. At a reactor power level of 250 thermal megawatts, the following machine characteristics would be required:

Working fluid: Helium
Suction temperature: 1,200° F.
Suction pressure: 431 p.s.i.a.
Discharge pressure: 441 p.s.i.a.
Flow through compressor: 76,000 actual c.f.m., 450,000 lb./hr.
Type: Multistage axial

The operating temperature of 1,200° F. is considerably above that of conventional compressor operation at the present time. However, a number of gas turbines are operating successfully at higher temperatures. At least one two-stage axial compressor has been built and tested for operation with air at 1,200° F. It is believed that an adaptation of this design to helium is feasible. Because of its lower molecular weight and density, helium requires several more compression stages. However, sonic velocity in helium is approximately 2.5 times that in air, which permits higher tip speeds for compressors operating with helium.

The major problem in designing the recycle compressor appears to be the rotating shaft seal. Although the helium itself does not become radioactive, it will contain some gaseous and solid radioactive fission products. For this reason, leakage must be held to an absolute minimum, although a very small amount of leakage could be tolerated. This leakage would be vented through a stack.

In lieu of a better seal, canning is under consideration. This technique consists of enclosing both the motor and compressor in a pressure vessel in an atmosphere of the fluid to be pumped. No seal is required. This technique has worked very well in recirculating water pumps for pressurized water reactors.

Due to the high temperature (1,200° F.) and the low molecular weight of helium, the compressor will operate under a high adiabatic head even at low

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compression ratios (fig. 5). This will necessitate high tip speeds on the compressor. (The relationship of peripheral velocity to developed head is approximately $v^2 = 2\ gh$, where v is the peripheral velocity of the impeller and h is the developed head.) The physical size of the equipment may be minimized by going to very high compressor speeds. Minimum size facilitates canning.

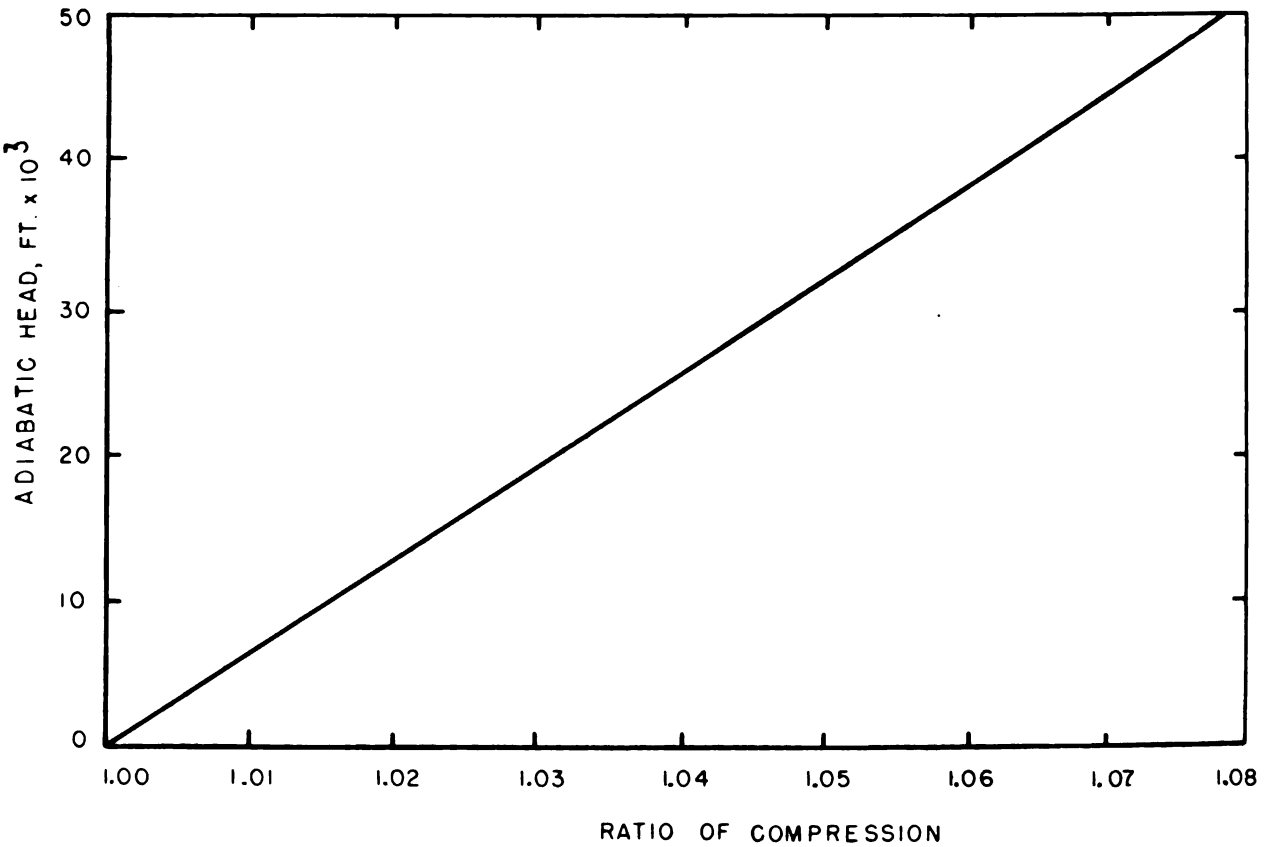

FIGURE 5. - Adiabatic Head for Helium at 1,200° F.

Inasmuch as high-frequency motors are available, the principal problems lie in adapting the motor to run in the helium environment and in the design of the compressor rotor.

Heat Exchanger

In a process-heat reactor system using a gaseous heat-transfer medium, a high-temperature heat exchanger is required. Such an exchanger would transfer heat from helium to the process streams to be reacted at temperatures in the 2,500° F. range. At present, an exchanger of this nature does not exist, and considerable research and development will be required for its eventual construction. Two concepts for this type of exchanger have been proposed.

The first concept would make use of molybdenum tubes coated on the outside with molybdenum disilicide. The helium would pass through the inside of the tubes; and the process streams, such as steam or air, would pass over the

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outside of the tubes. The use of molybdenum tubes would allow welding of headers and tube sheets. These techniques, when fully developed, promise to allow fabrication of a high-temperature heat exchanger that would have very low leakage of helium into the process streams.

Another approach to the problem of constructing a high-temperature exchanger would be the use of ceramics. Although past experience with ceramics has not been too encouraging due to gas leakage, there have been some significant developments recently, particularly with silicon carbide. Small silicon carbide tubes having high mechanical strength and capable of containing gases at 30 atmospheres in the 2,500° F. temperature range have been constructed and tested. Joining these tubes to headers and tube sheets to obtain gastight connections will be a major problem. However, preliminary results have indicated that the idea is feasible.

Once high temperatures have been attained in nuclear reactors, there will be a decided incentive to develop exchangers to utilize the nuclear heat.

To exploit nuclear heat to its fullest extent, high-temperature heat exchange will be necessary. There are processes, such as re-forming hydrocarbon gases and certain refining operations, that could be performed in stainless steel exchangers of current design, as the reactants keep the temperature of the tube walls externally heated by combustion products at a moderate level. Also, the life of the tubes will be longer when heated by a helium stream than by exposure to products of combustion.

PART II

Use of Nuclear Process Heat for Coal Gasification

To date, most of the studies conducted by the Bureau of Mines for utilizing process heat from nuclear reactors have been concerned with the gasification of coal. Use of a 250-megawatt reactor furnishing process heat in the form of helium at 2,700° F. for gasifying a low-rank coal is an interesting case study. Experimental work by the Bureau (1) has demonstrated the feasibility of gasifying finely powdered low-rank coals (subbituminous coals and lignite) in alloy-steel tubes at temperatures in the range of 1,800° F. It is believed that a gasifier for these low-rank coals would consist essentially of a heat exchanger for transferring the heat from a stream of recycled helium to a steam-coal mixture. Raising the operating temperature of such an exchanger to 2,000° F. or higher would materially aid the process but is not a necessity.

Since synthesis gas is normally utilized at pressures of 30 atmospheres or above, it is advantageous to generate the gas at elevated pressures. Operation of a coal gasification system at 30 atmospheres results in saving approximately 6 cents per m.c.f. of gas generated owing to elimination of compression costs.

A gas-cooled reactor appears adaptable to coal gasification, since the operating pressure of 30 atmospheres is favorable to both reactor and gasifier

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operation. With the helium and the steam-coal mixture at essentially the same pressure, the stresses in the heat-exchanger tubes would be minimized.

Heat-exchanger cost, which is expected to be a large item in such a system, is a function of the surface area required for heat transfer. With both the heat carrying gas and the reactants at 30 atmospheres, a considerable reduction in heat-transfer area can be accomplished, compared with operation at atmospheric pressure.

A typical process utilizing nuclear heat for gasifying low-rank coal would be carried out under the following conditions:

Coal and water in the ratio of 1.5 pounds of water to 1 pound of dry, ash-free (MAF) coal are introduced into a slurry mix tank (fig. 6). After suitable mixing the slurry is pumped through the preheater. In this vessel the water is vaporized, and the steam-coal mixture is preheated to 1,800° F. in alloy-steel tubes. The pressures of the steam-coal mixture and helium are nearly balanced, so that the tubes are subjected to very low stresses caused by differential pressure.

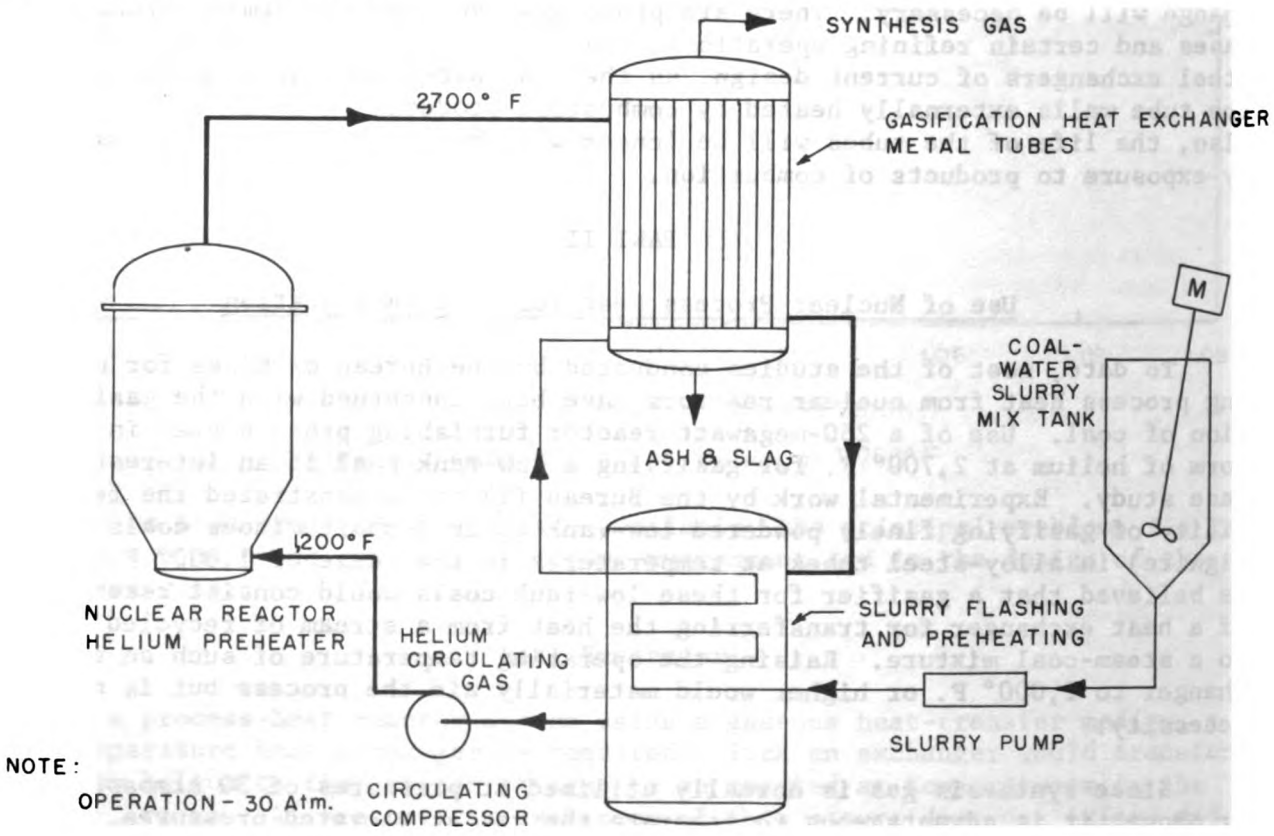

FIGURE 6. - Simplified Flowsheet for Nuclear Gasification.

From the preheater the steam-coal mixture enters the gasifier, where enough heat is added to react and thus gasify approximately 85 percent of the carbon contained in the coal, according to the reaction:

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$C + H_2O \rightarrow CO + H_2$ -58,000 B.t.u./lb. mol. carbon

The process heat required for vaporizing the water, preheating the resultant coal-steam mixture, and gasifying 85-percent of the carbon based on 1 pound of M.A.F. subbituminous coal is divided between the slurry preheater and the gasifier:

Heat Duty for Slurry Preheater

B.t.u. required for vaporizing water and superheating steam to 1,800° F. based on 1.5 lb. water/lb. coal

1.5 x 1,960	= 2,940	
Sensible heat of coal + ash	= 690	
Total	=	3,630

Heat Duty of Gasifier

Based on 85-percent gasification of a coal containing 77.2 percent carbon on M.A.F. basis

4,800 x 0.772 x 0.85	= 3,140 B.t.u.	3,140
Total B.t.u./lb. M.A.F. coal	=	6,770

Assuming an overall loss of 5 percent due to radiation, total heat required/lb. M.A.F. coal becomes 7,130 B.t.u.

Coal-gasifying capability of 250-megawatt nuclear reactor $= \frac{854 \times 10^6}{7,130}$ = 120,000 lb./hr.

Helium Temperatures

	°F.
Entering gasifier	2,700
Leaving gasifier	2,000
Entering slurry preheater	2,000
Leaving slurry preheater	1,190
Correcting for radiation and unaccounted-for thermal losses, final gas temperature becomes	1,100

The helium at approximately 1,100° F. is recycled to the reactor.

For gasification of higher rank coals, heat exchangers capable of operation in the range of 2,000° - 2,500° F. will be required. Gasification of these coals is attractive, and it is expected that development of such heat exchangers will be prosecuted as the general work on the nuclear-fueled system progresses.

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CONCLUSIONS

A nuclear reactor capable of supplying process heat in the form of recycled helium heated to 2,500° F. would require a step upward of approximately 1,500° F. in current reactor practice. However, there appear to be no inherent characteristics in the helium-carbon-uranium carbide system that would make it impossible to achieve these temperatures. Utilization of this heat to gasify a low-rank coal could be done in a heat exchanger constructed of the best existing commercial alloys. However, the extensive research program now being conducted to develop materials capable of operation at increasingly higher temperatures should result in raising the temperature limit for gasification. This would allow gasification of higher rank coals or chars made from these coals.

Use of a nuclear reactor to furnish the process heat required for gasifying coal is an interesting possibility, since it eliminates the need for process oxygen and therefore affords a potential reduction in the cost of producing synthesis gas.

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